Modeling and Analysis of Custom Power Systems by PSCAD/EMTDC

Olimpo Anaya-Lara and E. Acha

***Abstract*—This paper addresses the timely issue of modeling and analysis of custom power controllers, a new generation of power electronics-based equipment aimed at enhancing the reliability and quality of power flows in low-voltage distribution networks [2], [3]. The modeling approach adopted in the paper is graphical in nature, as opposed to mathematical models embedded in code using a high-level computer language. The well-developed graphic facilities available in an industry standard power system package, namely PSCAD/EMTDC, are used to conduct all aspects of model implementation and to carry out extensive simulation studies. Graphics-based models suitable for electromagnetic transient studies are presented for the following three custom power controllers: the distribution static compensator (D-STATCOM), the dynamic voltage restorer (DVR), and the solid-state transfer switch (SSTS). Comprehensive results are presented to assess the performance of each device as a potential custom power solution. The paper is written in a tutorial style and aimed at the large PSCAD/EMTDC user base.**

***Index Terms*—Custom power, distribution static compensator (D-STATCOM), dynamic voltage restorer (DVR), PWM, solid-state transfer switch (SSTS), voltage source converter.**

I. INTRODUCTION

THE last decade has seen a marked increase on the deployment of end-user equipment that is highly sensitive to poor quality control electricity supply. Several large industrial users are reported to have experienced large financial losses as a result of even minor lapses in the quality of electricity supply [2], [3], [8]. A great many efforts have been made to remedy the situation, where solutions based on the use of the latest power electronic technology figure prominently. Indeed, custom power technology, the low-voltage counterpart of the more widely known flexible ac transmission system (FACTS) technology, aimed at high-voltage power transmission applications, has emerged as a credible solution to solve many of the problems relating to continuity of supply at the end-user level. Both the FACTS and custom power concepts are directly credited to EPRI [1], [2].

At present, a wide range of very flexible controllers, which capitalize on newly available power electronics components, are emerging for custom power applications. Among these, the distribution static compensator (D-STATCOM) and the dynamic voltage restorer (DVR), both of them based on the VSC principle [6], and the SSTS are the controllers which have received the most attention. PSCAD/EMTDC [4], [5] has been used in this paper to perform the modeling and analysis of such controllers for a wide range of operating conditions.

PSCAD/EMTDC's highly developed graphical interface has proved instrumental in implementing the graphics-based PWM control reported in this paper for the D-STATCOM and DVR. It relies only on voltage measurements for its operation, i.e., it does not require reactive power measurements [7]. A sensitivity analysis is carried out to determine the impact of the dc capacitor size on D-STATCOM performance. In the case of the DVR, a constant dc source is assumed to provide the dc voltage; therefore, this analysis is not considered. With respect to the SSTS, the control scheme is implemented based on the detection of a fault condition developing in the energy supply system.

II. PSCAD/EMTDC SIMULATION TOOL

PSCAD/EMTDC is an industry standard simulation tool for studying the transient behavior of electrical networks. Its graphical user interface enables all aspects of the simulation to be conducted within a single integrated environment including circuit assembly, run-time control, analysis of results, and reporting. Its comprehensive library of models supports most ac and dc of power plant components and controls, in such a way that FACTS, custom power, and HVDC systems can be modeled with speed and precision. It provides a powerful resource for assessing the impact of new power technologies in the power network.

Simplicity of use is one of the outstanding features of PSCAD/EMTDC. Its great many modeling capabilities and highly complex algorithms and methods are transparent to the user, leaving him free to concentrate his efforts on the analysis of results rather than on mathematical modeling. For the purpose of system assembling, the user can either use the large base of built-in components available in PSCAD/EMTDC or to its own user-defined models. Indeed, the thrust of this paper is to share with the large PSCAD/EMTDC user community our user-defined models for custom power applications, which are not yet available as standard models within PSCAD/EMTDC. In this respect, one of the aims of the paper is to act as a tutorial in the subject of custom power modeling using PSCAD/EMTDC. For newcomers to the use of PSCAD/EMTDC, it is recommended that the very useful, generic examples available in [4] be well-understood and then the custom power circuits presented in the paper attempted.

To show the effectiveness and simplicity of the proposed models, the ac network modeling capabilities of PSCAD/EMTDC are simplified as much as practicable, such that

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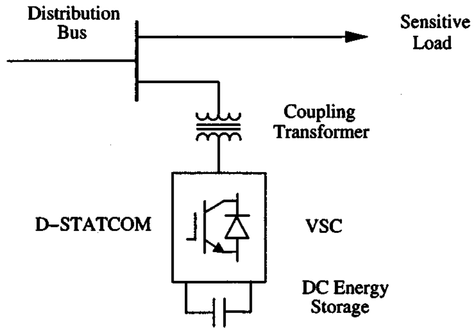


Fig. 1. Schematic representation of the D-STATCOM as a custom power controller.

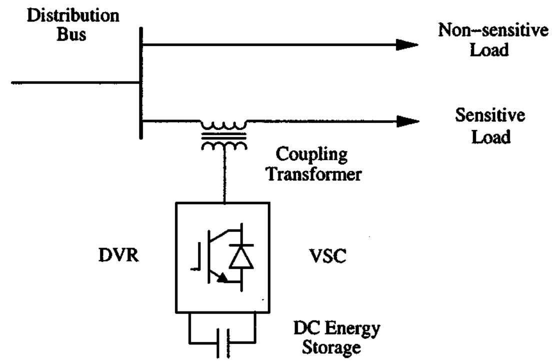


Fig. 2. Schematic representation of the DVR for a typical custom power application.

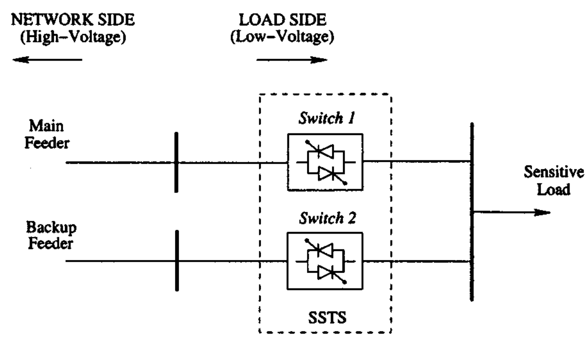


Fig. 3. Schematic representation of the SSTS as a custom power device.

standard features such as synchronous generator, transformer saturation, and frequency-dependent transmission line and cable models are not used in our test circuits.

III. VSC-Based Controllers

This section presents an overview of the VSC-based custom power controllers addressed in the paper.

A. D-STATCOM

In its most basic form, the D-STATCOM configuration consists of a two-level VSC, a dc energy storage device, a coupling transformer connected in shunt with the ac system, and associated control circuits [7]–[10]. More sophisticated configurations use multipulse and/or multilevel configurations [11], [12]. Fig. 1 shows the schematic representation of the D-STATCOM. The VSC converts the dc voltage across the storage device into a set of three-phase ac output voltages. These voltages are in phase and coupled with the ac system through the reactance of the coupling transformer. Suitable adjustment of the phase and magnitude of the D-STATCOM output voltages allows effective control of active and reactive power exchanges between the D-STATCOM and the ac system.

The VSC connected in shunt with the ac system provides a multifunctional topology which can be used for up to three quite distinct purposes [13], [19]:

1) voltage regulation and compensation of reactive power;
2) correction of power factor;
3) elimination of current harmonics.

The design approach of the control system determines the priorities and functions developed in each case. In this paper, the D-STATCOM is used to regulate voltage at the point of connection. The control is based on sinusoidal PWM and only requires the measurement of the rms voltage at the load point as explained in Section IV.

B. Dynamic Voltage Restorer

The DVR is a powerful controller that is commonly used for voltage sags mitigation at the point of connection [14]–[16]. The DVR employs the same blocks as the D-STATCOM, but in this application the coupling transformer is connected in series with the ac system, as illustrated in Fig. 2.

The VSC generates a three-phase ac output voltage which is controllable in phase and magnitude. These voltages are injected into the ac distribution system in order to maintain the load voltage at the desired voltage reference. The main features of the DVR control scheme implemented in this paper are explained in Section IV.

IV. Solid-State Transfer Switch

The SSTS can be used very effectively to protect sensitive loads against voltage sags, swells and other electrical disturbances [17], [18]. The SSTS ensures continuous high-quality power supply to sensitive loads by transferring, within a time scale of milliseconds, the load from a faulted bus to a healthy one. The basic configuration of this device consists of two three-phase solid-state switches, one for the main feeder and one for the backup feeder. These switches have an arrangement of back-to-back connected thyristors, as illustrated in the schematic diagram of Fig. 3.

Each time a fault condition is detected in the main feeder, the control system swaps the firing signals to the thyristors in both switches, i.e., *Switch 1* in the main feeder is deactivated and *Switch 2* in the backup feeder is activated. The control system measures the peak value of the voltage waveform at every half-cycle and checks whether or not it is within a prespecified range. If it is outside limits, an abnormal condition is detected and the firing signals to the thyristors are changed to transfer the load to the healthy feeder.

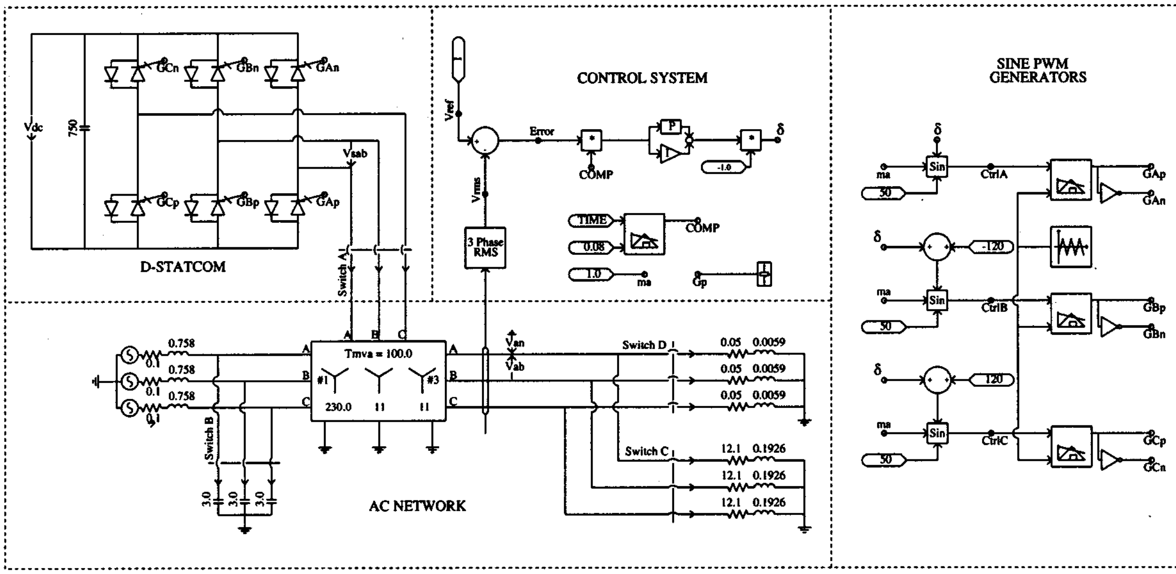


Fig. 4. Control scheme and test system implemented in PSCAD/EMTDC to carry out the D-STATCOM simulations.

V. Sinusoidal PWM-Based Control

This section describes the PWM-based control scheme with reference to the D-STATCOM. The control scheme for the DVR follows the same principle. The aim of the control scheme is to maintain constant voltage magnitude at the point where a sensitive load is connected, under system disturbances. The control system only measures the rms voltage at the load point [7], i.e., no reactive power measurements are required [9]. The VSC switching strategy is based on a sinusoidal PWM technique which offers simplicity and good response. Since custom power is a relatively low-power application, PWM methods offer a more flexible option than the fundamental frequency switching (FFS) methods favored in FACTS applications. Besides, high switching frequencies can be used to improve on the efficiency of the converter, without incurring significant switching losses. Fig. 4 shows the test system and D-STATCOM controller implemented in PSCAD/EMTDC. The D-STATCOM control system exerts voltage angle control as follows: an error signal is obtained by comparing the reference voltage with the rms voltage measured at the load point. The PI controller processes the error signal and generates the required angle δ to drive the error to zero, i.e., the load rms voltage is brought back to the reference voltage. In the PWM generators, the sinusoidal signal $v_{control}$ is phase-modulated by means of the angle δ. The modulated signal $v_{control}$ is compared against a triangular signal (carrier) in order to generate the switching signals for the VSC valves.

The main parameters of the sinusoidal PWM scheme are the amplitude modulation index m_a of signal $v_{control}$, and the frequency modulation index m_f of the triangular signal. The amplitude index m_a is kept fixed at 1 pu, in order to obtain the highest fundamental voltage component at the controller output [19], [20]. The switching frequency m_f is set at 450 Hz, $m_f = 9$. It should be noted that, in this paper, balanced network and operating conditions are assumed. The modulating angle δ is applied to the PWM generators in phase A. The angles for phases B and C are shifted by 240° and 120°, respectively. It can be seen in Fig. 4 that the control implementation is kept very simple by using only voltage measurements as the feedback variable in the control scheme. The speed of response and robustness of the control scheme are clearly shown in the simulation results.

VI. Test Cases

This section is divided into three parts. Simulations relating to the D-STATCOM are presented first. This is followed by simulations carried out for the DVR and then for the SSTS. Comprehensive results are presented to assess the performance of each device as a Custom Power solution.

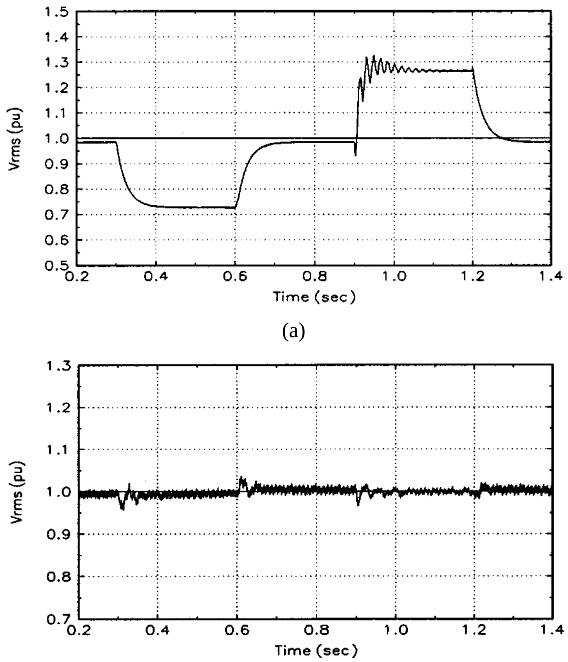
A. D-STATCOM Simulations and Results

Fig. 4 shows the test system implemented in PSCAD/EMTDC to carry out simulations for the D-STATCOM. The test system comprises a 230 kV transmission system, represented by a Thévenin equivalent, feeding into the primary side of a 3-winding transformer. A varying load is connected to the 11 kV, secondary side of the transformer. A two-level D-STATCOM is connected to the 11 kV tertiary winding to provide instantaneous voltage support at the load point. A 750 μF capacitor on the dc side provides the D-STATCOM energy storage capabilities.

The set of switches shown in Fig. 4 were used to assist different loading scenarios being simulated with ease. To show the effectiveness of this controller in providing continuous voltage regulation, simulations were carried out with and with no D-STATCOM connected to the system.

A set of simulations was carried out for the test system shown in Fig. 4. The simulations relate to three main operating conditions.

1) In the simulation period 300–600 ms, the load is increased by closing *Switch D*. In this case, the voltage drops by almost 27% with respect to the reference value.



(a)

(b)

Fig. 5. Voltage $V_{\rm rms}$ at the load point: (a) with no D-STATCOM and (b) with D-STATCOM; capacitor size: 750 μF.

2) At 600 ms, the *switch D* is opened and remains so throughout the rest of the simulation. The load voltage is very close to the reference value, i.e., 1 pu.
3) In the simulation period 900–1200 ms, *Switch B* is closed, connecting a capacitor bank to the high voltage side of the network. The rms voltage increases 27% with respect to the reference voltage.

Fig. 5(a) shows the rms voltage at the load point for the case when the system operates with no D-STATCOM. Similarly, a new set of simulations was carried out but now with the D-STATCOM connected to the system. The results are shown in Fig. 5(b), where the very effective voltage regulation provided by the D-STATCOM can be clearly appreciated. When the *Switch D* closes, the D-STATCOM supplies reactive power to the system, and when *Switch D* opens and *Switch B* closes, the D-STATCOM absorbs reactive power in order to get the voltage back to reference. In spite of sudden load variations, the regulated rms voltage shows a reasonably smooth profile, where the transient overshoots are almost nonexistent. The magnitude of these transients is kept within $\pm$5% with respect to the reference voltage. In fact, they do not last for more than two cycles.

1) Capacitor Sizing Based on Simulations: In order to gain insight into the influence that capacitor size has on D-STATCOM performance, several simulations were carried out in PSCAD/EMTDC using the same test system and operating conditions as those used in the previous section. Extensive simulations were carried out to identify the most suitable capacitor size, aiming at minimizing waveform distortion and keeping transient overshooting at minimum values. It should be noted that no filters have been included in the test circuit in order to gain a better understanding of the role that capacitor size plays on harmonic distortion generation.

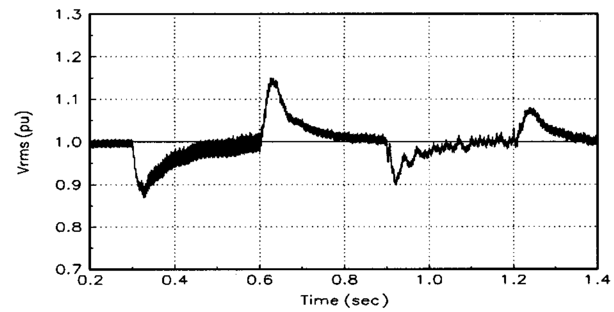


Fig. 6. Voltage $V_{\rm rms}$ at the load point with D-STATCOM; capacitor size: 75 μF.

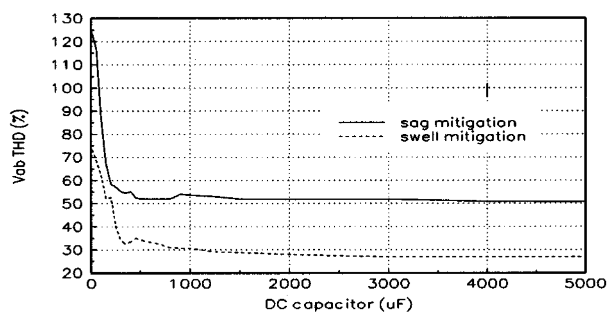


Fig. 7. Influence of capacitor size on D-STATCOM harmonic generation.

By way of example, Fig. 5(b) shows the regulated rms voltage corresponding to a 750 μF capacitor, where a rapid regulation response is obtained and transient overshoots are almost nonexistent. This contrasts with cases where the capacitor is undersized. For instance, Fig. 6 shows the rms voltage for the case when a 75 μF capacitor is employed.

A sluggish response and large transient overshoots are observed, together with high harmonic distortion and unrealistic voltage ripple in the dc capacitor. In order to characterize further the impact of capacitor size on harmonic generation, extensive simulation results were performed to aid these investigations. Fig. 7 presents a summary of results where capacitor sizes ranging from 5 to 5000 μF, with 25 μF step sizes, were employed. It has been observed that the D-STATCOM exhibits a very different harmonic generation behavior when it acts as a source of reactive power than when it draws reactive power from the ac system. Hence, two plots are shown in Fig. 7, where a consistently lower voltage total harmonic distortion (VTHD) is present when the D-STATCOM draws reactive power from the ac system (swell mitigation). It can be observed from this figure that there is a point when further increases in capacitor size do not yield any further VTHD reductions.

B. DVR Simulations and Results

Fig. 8 shows the test system used to carry out the various DVR simulations presented in this section. The DVR coupling transformer is connected in delta in the DVR side, with a leakage reactance of 10%. A unity transformer turns ratio was used, i.e., no booster capabilities exist. The capacity of the dc storage device is 5 kV. Two simulations are carried out as follows.

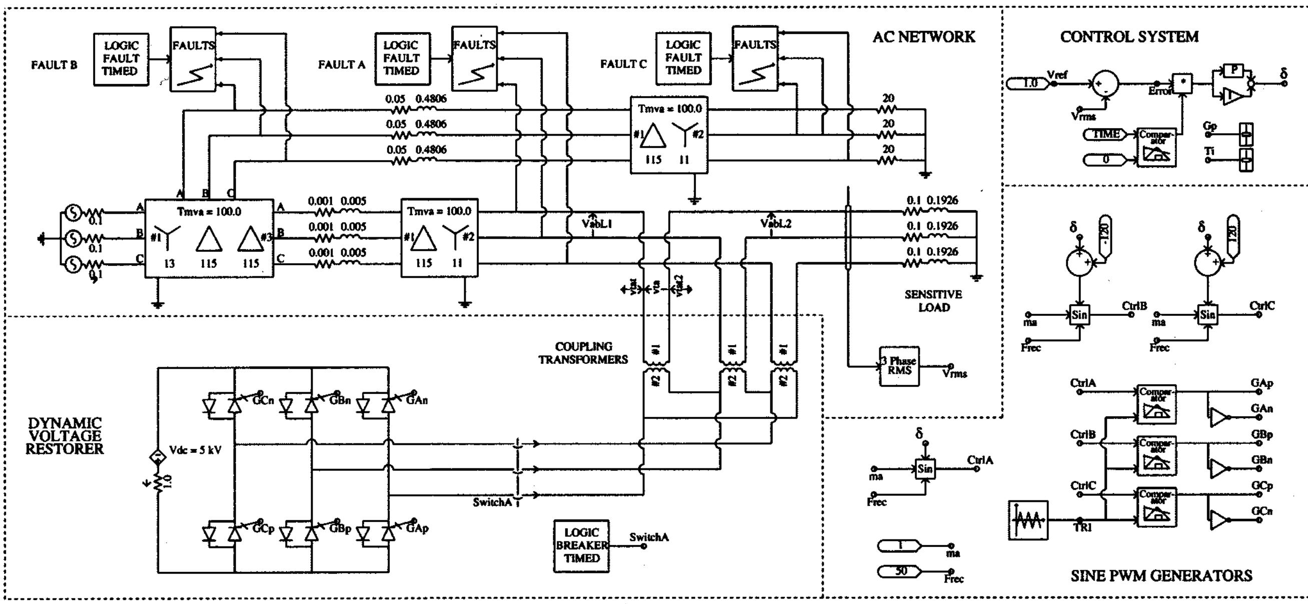
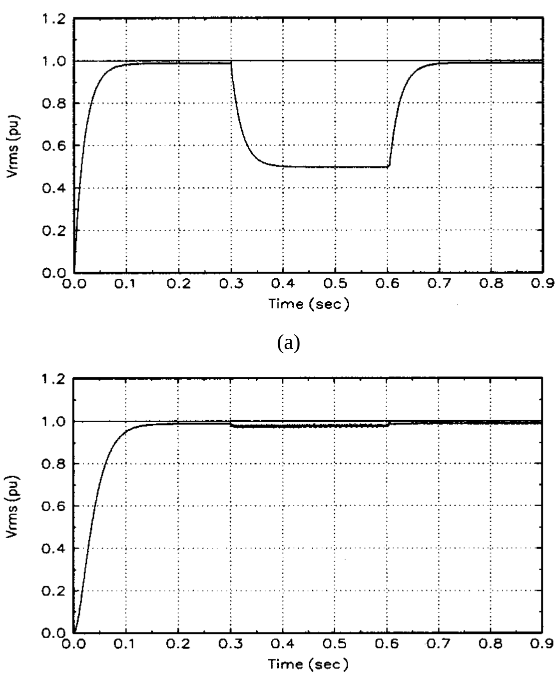


Fig. 8. Control scheme and test system implemented in PSCAD/EMTDC to carry out the DVR simulations.



(a)

(b)

Fig. 9. Voltage $V_{\rm rms}$ at the sensitive load point: (a) with no DVR and (b) with DVR.

1) The first simulation contains no DVR and a three-phase short-circuit fault is applied at point **A**, via a fault resistance of 0.66 Ω, during the period 300–600 ms. The voltage sag at the load point is 50% with respect to the reference voltage.
2) The second simulation is carried out using the same scenario as above but now with the DVR in operation.

The total simulation period is 900 ms. Using the facilities available in PSCAD/EMTDC, the DVR is simulated to be in operation only for the duration of the fault, as it is expected to be the case in a practical situation. The results for both simulations are shown in Fig. 9. When the DVR is in operation the voltage sag is mitigated almost completely, and the rms voltage at the sensitive load point is maintained at 98%, as shown in Fig. 9(b).

The PWM control scheme controls the magnitude and the phase of the injected voltages, restoring the rms voltage very effectively. The sag mitigation is performed with a smooth, stable, and rapid DVR response; no transient overshoots are observed when the DVR comes in and out of operation. It should be noted that in the DVR, the dc voltage is supplied by a dc source as opposed to the dc capacitor used in the D-STATCOM. Several simulations were carried out to assess the performance of the DVR as a function of short-circuit proximity. Three-phase faults via fault resistances were applied at the A, B, and C points shown in the test system of Fig. 8. As expected, the DVR required a higher rating of dc storage device to provide appropriate levels of sag mitigation when the fault was applied in point A. This is due to the short electrical distance between the point in fault and the DVR coupling transformer. Clearly, the controller must be designed to satisfy the most stringent case, i.e., the voltage sag is generated by a fault occurring quite close to the sensitive load.

C. SSTS Simulations and Results

Fig. 10 shows the test system used to carry out the SSTS simulations. The system comprises two identical feeders feeding into a 13 kV-busbar. A sensitive load is connected to the busbar. The following simulations were carried out to assess the effectiveness of the simple control scheme proposed in this paper for the SSTS:

1) in the first experiment the SSTS is disconnected and a three-phase fault is applied at the main feeder at a time 310 ms, with a fault duration of 200 ms. The magnitude of the voltage sag due to the fault is 30%, as seen from the rms voltage shown in Fig. 11(a);

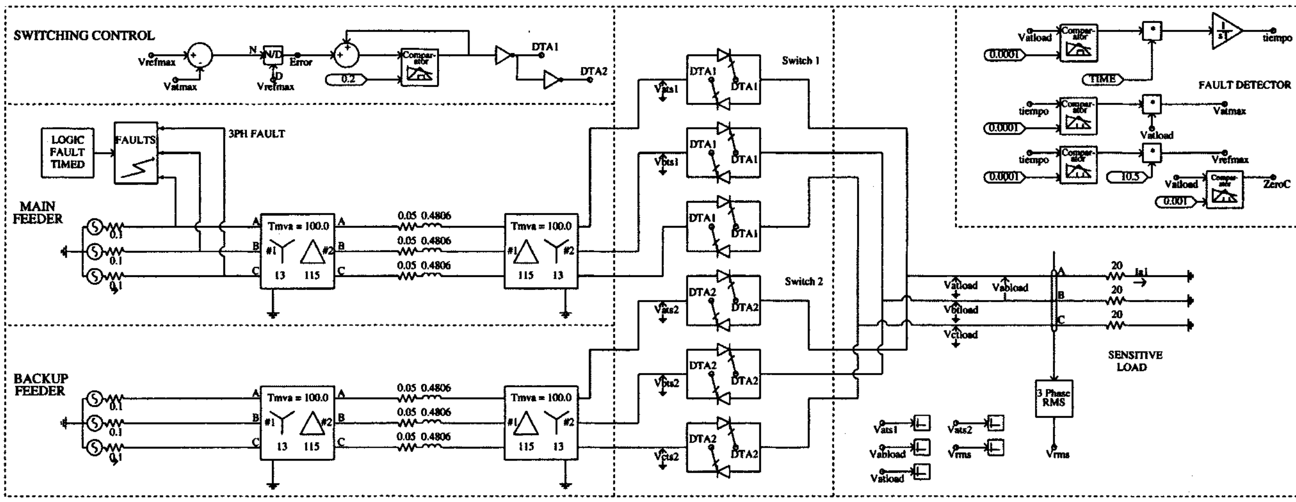


Fig. 10. Control scheme and test system implemented in PSCAD/EMTDC to carry out the SSTS simulations.

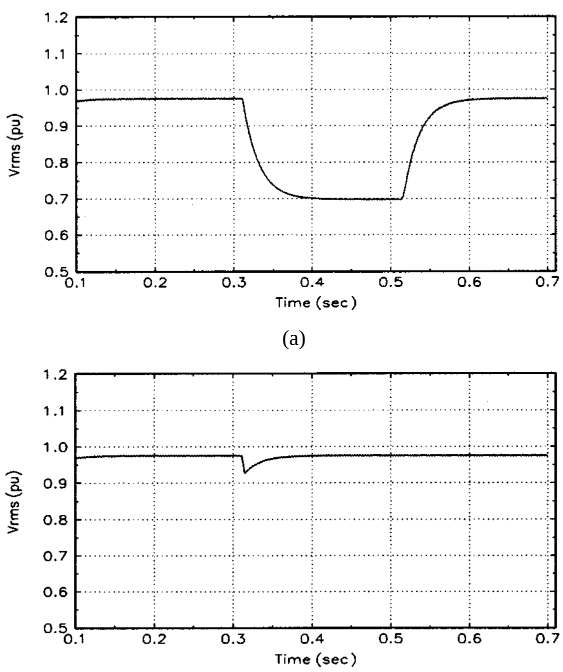


Fig. 11. Voltage $V_{\rm rms}$ at the load point: (a) with no SSTS and (b) with the SSTS connected.

2) a second experiment was carried out using a similar scenario as above but now with the SSTS in operation. The rms voltage at the load point is shown in Fig. 11(b).

The total period of simulation is 700 ms. In the simulations presented here, the control system monitors the maximum and minimum values of the voltage waveform at the load point every half-cycle. Whenever a faulted condition in the electrical supply is detected, the triggering signals to both three-phase switches are reversed. Fig. 11(b) shows that after the disturbance has occurred the rms voltage at the load point is driven back to the prefault value very rapidly. It should be noted that the SSTS does not regulate voltage neither generate/absorb reactive power, its only function is to deactivate a faulty feeder in favor of a healthy one. The waveform of the voltage V_{ab} at the load point is shown in Fig. 12.

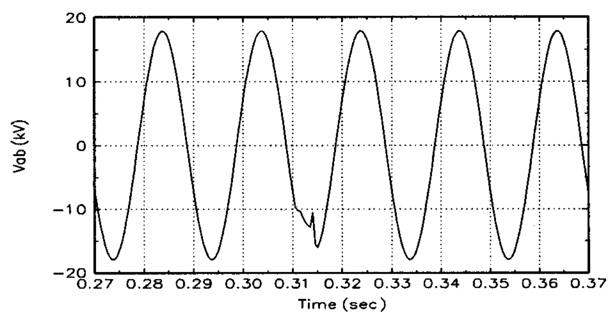


Fig. 12. Waveform of the voltage V_{ab} at the load point when the SSTS is in operation.

It can be seen that when the faulted condition is registered, it only takes a fraction of a cycle (less than 4 ms at 50 Hz fundamental frequency) for the SSTS to perform the transfer of load to the backup feeder, and restore the voltage to the prefault condition. Arguably, there is always a load transfer delay associated with SSTS applications which is a function of the fault detection technique used. In our case, the health of the voltage waveform is checked at every peak and trough, with respect to a reference voltage value, e.g., 90% of rated value. In alternative schemes reported in the open literature, the delay incurred is higher than 1/4 of a cycle owing to the need to perform a Fourier analysis of the voltage waveform [18]. In our SSTS scheme, if a more stringent load transfer criteria is required then the sampling period can be reduced with ease. The technique does not require complicated software implementations. Monitoring the voltage at peak values reduces the possibility of the control scheme being adversely affected by the presence of strong harmonic distortion.

VII. Conclusions

This paper has presented electromagnetic transient models of custom power equipment, namely D-STATCOM, DVR, and SSTS, and applied them to the study of power quality. The highly developed graphic facilities available in PSCAD/EMTDC were used to conduct all aspects of model implementation and to carry out extensive simulation studies. A new PWM-based control scheme has been implemented to control the electronic valves in the two-level VSC used in the D-STATCOM and DVR. As opposed to fundamental frequency switching schemes already available in the PSCAD/EMTDC, this PWM control scheme only requires voltage measurements. This characteristic makes it ideally suitable for low-voltage custom power applications. The control scheme was tested under a wide range of operating conditions, and it was observed to be very robust in every case. Extensive simulations were conducted to gain insight into the impact of capacitor size on D-STATCOM harmonic generation, speed of response of the PWM control and transient overshooting. It was observed that an undersized capacitor degrades all three aspects. On the other hand, an oversized capacitor may also lead to a PWM control with a sluggish response but it will reduce D-STATCOM harmonic generation and transient overshooting. It was observed that there is a point when increasing the size of capacitor does not reduce VTHD any further.

The simulations carried out showed that the DVR provides excellent voltage regulation capabilities. It was observed that its capacity for power compensation and voltage regulation depends mainly on two factors: the rating of the dc storage device and the characteristics of the coupling transformer. These two factors determine the maximum value of sag mitigation that the DVR can provide. The SSTS proved to be a suitable device for screening selected load points against faulted conditions, but it does require an alternative feeder being available. The transfer of load from a faulted feeder to a healthy one can be achieved in a short period of time. The fault detection technique used in the paper is very simple and yet has proved to yield very effective results.

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